July 20, 1965

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

A STUDY OF THE CONTRIBUTIONS OF FLAP- AND SIDE-PANELS IN END-TO-END BOX COMPRESSION

✓ Project 1108-4

A Preliminary Report

to

TECHNICAL DIVISION
FOURDRINIER KRAFT BOARD INSTITUTE, INC.

July 9, 1965

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SUMMARY

A study of the effect of box dimensions on end-load compression was performed for the purpose of studying the adequacy of a previously developed formula for estimating end-load compression strength. To gain a better understanding of the behavior of the two types of load-bearing panels in end-to-end compression (flap panels and side panels), an experimental method was devised to render one type of panel inactive in the load-bearing sense so that the load carried by the other type of panel could be measured during the compression test. The method consisted of cutting either a pattern of circular holes or a horizontal slot in the unwanted panel.

On the average, the sum of the loads on the flap- and side-panels, determined in this way, was 14% less than the observed compression strength of the corresponding box. This result indicates that the experimental method of isolating flap- and side-panel behavior does not yield absolute magnitudes of panel loads (perhaps because any degree of cutout of the panels sacrifices some of the structural integrity of a box). However, it is believed that the trends observed in this study serve as a useful guide to understanding the behavior of flap panels and side panels in a normal box.

The following effects were noted from the results of tests on a sample of A-flute, 175-lb. series and a sample of B-flute, 275-lb. series combined board (representing reasonable extremes of strength in end-to-end compression).

EFFECT OF VARYING BOX LENGTH AT CONSTANT WIDTH AND DEPTH

1. The load carried by the side panels at the time of box failure is independent of the box length. This result is compatible with the observation that the side panel crushes at the loading perimeter and thus reflects local crushing at a body scoreline rather than panel height (box length).

2. The strength of the flap panels, and consequently of the entire box in end-load compression, decreases with increasing box length, because of the increase in the gap between inner flaps.

3. The assumptions made in deriving the box formula are compatible with these observations.

EFFECT OF VARYING BOX DEPTH AT CONSTANT LENGTH AND WIDTH

4. The load carried by the side panels increases linearly with increase in box depth, but is not directly proportional to depth as has been assumed.

5. The term $2fP_{mx}d$ in the formula, representing the contribution of the side panels to box strength, appears to be appropriate with respect to previously reported values of the constant f and the dependence on P_{mx} and d. However, the side-panel term should be modified to:

$$2fP_{mx}d + q\ P_{mx}$$

where q is a constant in the range of approximately 2.7 to 2.9, in order to agree with the observed loads in this study.

EFFECT OF VARYING BOX LENGTH AND WIDTH PROPORTIONALLY AT CONSTANT DEPTH

6. Flap-panel load, and consequently end-to-end box compression strength, increases with increasing box length and width (at constant ratio of width-to-length of 0.75 and constant box depth). This result indicates that the effect of increasing the loading perimeter of the flap panel dominates the effect of increasing the gap between inner flaps.

7. The end-load formula is in agreement with the aforementioned trend.

The end-load formula consistently (a) underestimated the side-panel load, (b) overestimated the flap-panel load, and (c) underestimated the box compression strength of the samples of this study. The proposed modification of the side-panel term of the formula [see Item (5) above] may rectify the errors in estimating side- and flap-panel loads. The systematic underestimation of box compression is believed to be associated with a higher level of box performance in the present study, relative to earlier work, as a result of improved sealing of the box flaps.

The results of the present study indicate that side panels carry somewhat greater loads and the flap panels less load than heretofore had been believed. This study indicates that in a box of equal width and depth, the flap panels contribute about two-thirds and the side panels about one-third of the box compressive strength.

The results of this study lend confidence to the structure of the end-load compression formula in so far as dimensions are concerned (and in the role of $\underline{P}_{mx}$ in the side-panel term). However, a modification of the side-panel term

INTRODUCTION

While top-to-bottom compression has received greater attention in the evaluation and analysis of the quality of corrugated boxes, end-to-end compression may be important in many applications. Resistance of the container to end-to-end impacts or shocks in a moving vehicle or on a conveyor, for example, may be expected to be related to the end-to-end compression strength of the box.

The over-all objective of this study is to develop an equation relating end-to-end compression strength of RSC boxes to combined board (or component) properties and box dimensions. It is hoped that the equation will have simplicity and applicability comparable to the formula which has been developed for top-load compression. The results of this work may be expected to find application in the definition and required magnitude of those properties of linerboard and medium that are important to good box performance.

Initial work (1) in this area resulted in an end-load equation based largely on theoretical considerations, as shown in Equation (1):

$$P = 0.30P_{mx}d + 3.10P_{mx}^{0.787}\left(\sqrt{D_xD_y}\right)^{0.213}(1 + W/L)^{0.512}\ W^{0.574} \qquad (1)$$

where P = end-to-end box compression strength, lb.

P_{mx} = machine-direction edgewise compression strength of combined board (evaluated by short column), lb./in.

D_x, D_y = flexural stiffnesses of combined board in machine and cross-machine directions, respectively, lb.-in.

L = box length, in.

W = box width, in.

d = box depth, in.

The first term on the right-hand side of Equation (1) pertains to the load supported by the two "side panels" of the box, such as panel CBEF in Fig. 1. The second term pertains to the contribution from the "flap panels" (Panel ABCD in Fig. 1). In general, the flap panels contribute the greater portion to the total load on the box, and it has been found that failure of the combined board of the outer flaps in the area between the inner flaps triggers failure of the box.

The factor $(1 + W/L)^{0.512}$ in the second term is a semiempirical accounting of the effect of flap gap (l); essentially it is a modification of the composite flexural stiffness, $\sqrt{D_x D_y}$, to account for the fact that when there is a gap between inner flaps, the flexural stiffness of the panel lies intermediate between that of a single- and a double-thickness of corrugated board. The remainder of the second term closely resembles the expression for load supported by a panel in top-load compression, even to the magnitude of the exponents (except of course that P_{mx} rather than P_m is involved).

The side-panel term of the formula (first term on the right-hand side) reflects two assumptions, namely, that (a) the load carried by a side panel is proportional to the loading "perimeter" of the panel, d, and (b) the intensity of load on the side panel is a fractional part of the edgewise compression strength of the combined board. The latter assumption is prompted by the observation that the side panels crush at the body scoreline (loading perimeter) and may involve, therefore, a mechanism of failure similar to machine-direction edgewise compression, namely, buckling of liner between the flute tips.

It should be remarked that edgewise compression strength of combined board in the machine-direction, P_{mx}, plays the dominant role in the end-load formula, as does the cross-direction strength, P_m, in top-load compression.

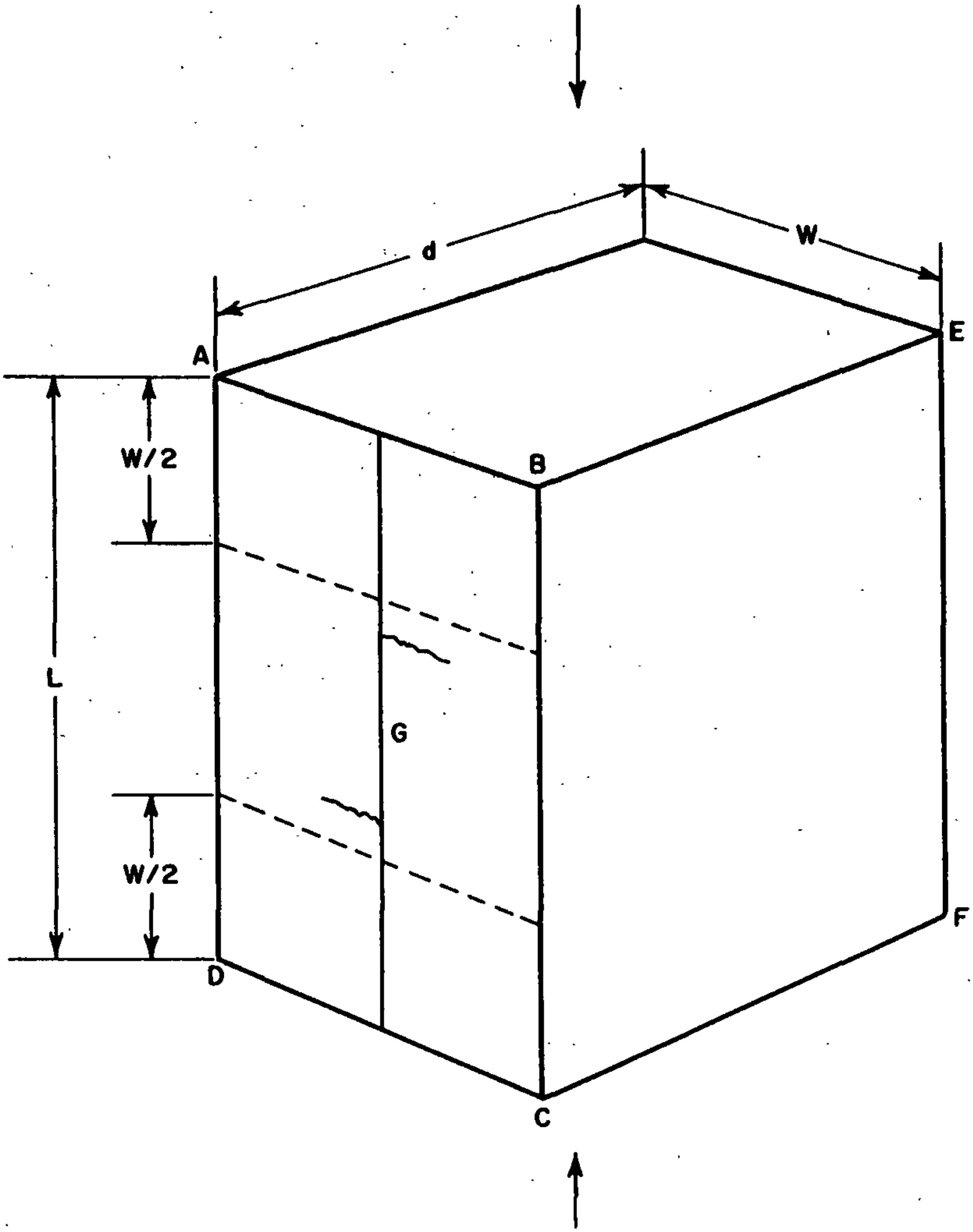

Figure 1. RSC Box in End-to-End Load Orientation

Equation (1) appears to be in qualitative agreement with the known behavior of boxes in end-load compression, for example, the relative performance of A-, B-, and C-flute constructions, the effect of the length of the gap between the inner flaps, and the effect of the loading perimeter dimensions $\underline{W}$ and $\underline{d}$.

The accuracy of Equation (1) was found to be about 8%, on the average, for the collection of samples for which it was derived. This accuracy is not as high as that for the top-load compression formula with the same collection of samples, namely, about 6%, on the average. The lower accuracy of the end-load formula may be attributed in part to statistical effects, namely, that the variability of end-load compression is typically about 40% higher than top-load; however, only half as many end-load compression specimens were available for testing in this program (ideally about twice the number of top-load specimens should have been tested in end-load to obtain equal confidence in the average compression strengths in the two orientations).

Statistical effects notwithstanding, it was felt that further study should be undertaken to gain a better understanding of end-to-end compression behavior, with the hope of improving the structure and/or the application of the formula.

As a first approach, attention was directed to the evaluation of $\underline{P}_{\underline{mx}}$ in view of its apparent dominant role in end-load compression. It appeared during the earlier work that the methodology of the machine-direction edgewise compression test of combined board was not fully satisfactory, as evidenced by considerable rolling and bending of the loading edges despite their reinforcement with Mobilwax D paraffin. The short column specimen used is 4-1/2 flutes high and two inches wide, with the loading edges reinforced to a depth of one flute by dipping in molten paraffin (1). Satisfactory behavior of the specimen is believed to be buckling of the liner between flute tips in the unreinforced portion of the specimen — this behavior corresponds to visible failure of the board in the flap panel of the box. Insufficient reinforcement of the loading edges of the column specimen, however, results in the unsatisfactory mode of failure mentioned above.

A number of harder formulations for edge reinforcement were tried and it was found that Carbowax 4000 (melting point 200°F., approximately) offered real improvement over Mobilwax D (2). With 52 samples of board, the maximum load with Carbowax was 23% higher, on the average, than with Mobilwax D, satisfying one criterion for an improved test. Moreover, the mode of specimen failure was generally favorable (buckling between flute tips). [An exception to the latter was the sturdier boards — for example, B-flute, 275-lb. series — where edge roll occurred occasionally even with the harder reinforcement. Further improvement in methodology is being sought for such constructions.]

In view of the major improvement in evaluation of $\underline{P_{mx}}$ and its possible effect on estimating end-load performance, the numerical constants in the end-load formula were rederived in terms of the Carbowax 4000 column data, giving the following equation (2):

$$P = 0.26P_{mx}d + 2.29P_{mx}^{0.785}\left(\sqrt{D_xD_y}\right)^{0.215}(1 + W/L)^{0.754}\ W^{0.571} \qquad (2)$$

Contrary to expectations, however, the average accuracy of estimating box strength by means of Equation (2) was not materially better than with the earlier Equation (1) — 8.2 vs. 8.6%, respectively, when applied to 43 box samples common to both studies. It appears that while the Carbowax specimen gives an improved test, in the sense of accuracy, the results of the two types of tests are correlated sufficiently well that there is no marked improvement in predicting box compression strength.

[A result of interest in connection with the study of P_{mx} is that this property of combined board depends upon the machine-direction flexural stiffness, EI, of the liners and the distance between flute tips (2). Thus, machine-direction strength of combined board depends upon the prerupture flexure property of the liners. This is different from cross-direction combined board strength, P_m, which depends upon the edgewise compression strength of the liners and medium. These results indicate that the linerboard manufacturer should be concerned with flexural stiffness (e.g., Taber stiffness) in the machine-direction of linerboard for end-to-end compression performance, and cross-direction edgewise compression strength (e.g., modified ring compression) for top-to-bottom compression strength.]

At this point it was felt that any marked improvement in the formula would probably come from a better understanding of the behavior of the box during end-load compression and consequent modification of the functional form of the equation. Further study was directed, therefore, to the "make-up" of the formula.

One of the most troublesome points in deriving an end-load formula has been that two differing types of panels are involved (flap panels and side panels), but from compression test data on the entire box it is impossible to know the relative contribution of either type of panel. This makes it difficult to assess the effectiveness of the separate terms in the formula relating to the two types of panels. To help overcome this difficulty, a method of experimentation was devised wherein one type of panel is rendered inactive in the load-bearing sense obtained by cutting either a pattern of circular holes or a horizontal slot in the panel such that load could not be passed through the panel.

This report describes a series of experiments performed in the above manner to help elucidate the behavior of each type of panel. The greater emphasis was placed on side-panel behavior, because it was believed that the assumptions made earlier about its behavior were needful of study. The study may be characterized as basically a "dimension" study in that a variety of box sizes were tested but only two combined board constructions were used.

MATERIALS

The boxes used in the study of flap- and side-panel behavior were fabricated at The Institute of Paper Chemistry from two lots of sheet stock procured from the Menasha Corporation, Menasha, Wisconsin. One lot was A-flute, 175-lb. series and the other was B-flute, 275-lb. series; the board was corrugated as a part of normal commercial production.

The choice of A-flute, 175-lb. and B-flute, 275-lb. boards was made on the basis that these constructions represent reasonable extremes from the standpoint of P_{mx}, the dominant factor in end-load compression. The B-flute sample has high P_{mx} because of the heavy liners and small flute pitch, while the A-flute, 175-lb. board has low P_{mx} for the converse reasons.

TEST PROCEDURE

After standard conditioning, RSC box blanks were made on the Institute slitter-scorer to the dimensions shown in Table I. Standard scoreline allowances were used. The flap scores were made with 3-point wheels, and the body scores with a V-male and a flat female. The scoring wheel clearances were set to the sum of the nominal thicknesses of the three components plus 0.005 in. Ten boxes for each flute combination were prepared for each condition listed in Table I, e.g., in the case of Sample 2, ten boxes were prepared for the regular end-load box test, ten for testing flap panels and ten for side panels.

TABLE I

DIMENSIONS OF BOXES FOR STUDY OF FLAP- AND SIDE-PANELS

Sample No.	Length, L, in.	Width, W, in.	Depth, d, in.	Box Test	Flap Panel	Side Panel
1	12	9	10	x	x	-
2	16	12	10	x	x	x
3	20	15	10	x	x	-
4	10	7.5	10	x	x	-
5	12.5	12	10	x	x	x
6	20	12	10	x	x	x
7	24	12	10	x	x	x
8	16	12	6	x	-	x
9	16	12	16	x	-	x
10	16	12	22	x	-	x
11	12.5	12	6	x	-	x
12	12.5	12	22	x	-	x
13	24	12	6	x	-	x
14	24	12	22	x	-	x

The selection of box dimensions was made on the basis of the discussion on p. 24 and 25 of Reference (1). Of the four cases of dimensional variation discussed there, three were selected for this study. They are:

1. Effect of box length at constant width and depth: Samples 2, 5, 6, 7, 8, 10, 11, 12, 13, 14.

2. Effect of box depth at constant length and width: Samples 2, 5, 7, 8, 9, 10, 11, 12, 13, 14.

3. Effect of varying box length and width at constant ratio $\underline{W}/\underline{L} = 0.75$ and at constant depth: Samples 1, 2, 3, 4.

For those boxes which were to be evaluated for flap-panel strength, the side panels were rendered inactive by cutting a number of five square-inch circular holes in the side panels by means of a flat crush circular specimen cutter, as indicated in Fig. 2. In addition, a strip of 1 by 1-inch lumber was placed between the testing machine platen and each loading edge of the flap panel during test, whereas no such strip was used on the side panels. The combination of holes and lumber permits load to act only in the flap panels. It may be remarked that the holes in the side panel leave sufficient material in that panel to "tie together" the flap panels and thereby give them lateral edge support similar to an intact box. (It was found in preliminary trials that removing the entire side panel, for example, sacrificed the edge support of the flap panel and it behaved differently during test relative to its behavior in an intact box.)

For tests of side-panel strength, the flap panels were made inactive by cutting a 3/4-inch wide slot across the flap gap area at mid-height, as illustrated in Fig. 3. A slot was used because cutting circular holes in the

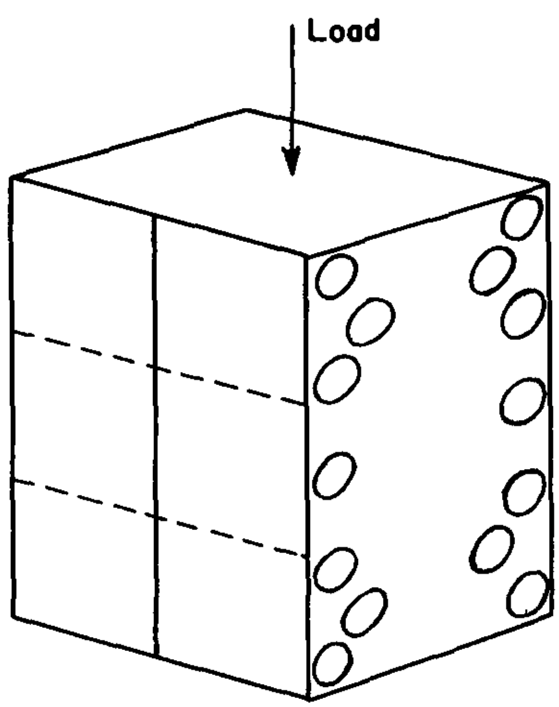

Figure 2. Preparation of Boxes for Study of Flap-Panel Behavior

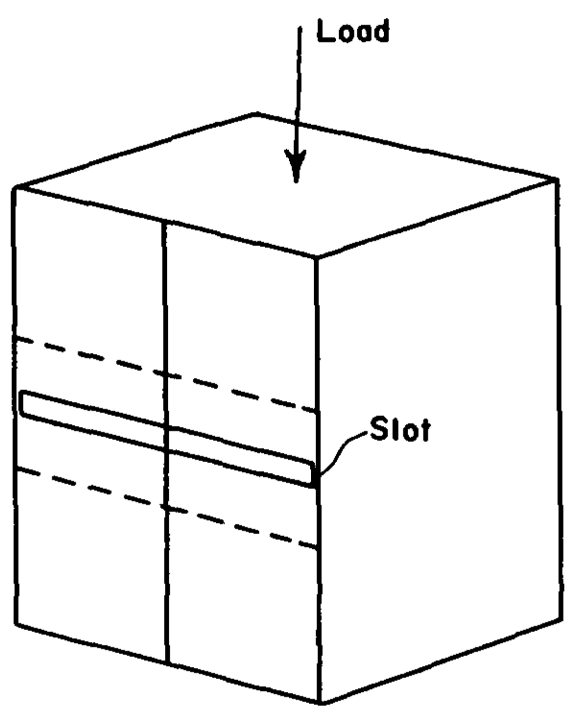

Figure 3. Preparation of Boxes for Study of Side-Panel Behavior

double-thickness flaps of A-flute boxes proved to be difficult. Strips of lumber were placed on the loading edges of the side panels during the compression testing.

The cutting of holes for inactivating the side panels was done after scoring and the cutting of slots to inactivate the flap panels after sealing the box. The manufacturer's joint was made with cloth-backed tape. The method of sealing the flaps prior to test represented a slight departure from usual laboratory procedure. The normal method involves applying silicate to the inner flap to within 1/2 inch of each edge. In the present study the adhesive was applied over the entire inner flap (exclusive of scorelines) and also over the corresponding area of the outer flap. This method was arrived at from observation that adhesive on both inner and outer flaps leads to more reliable adhesion and also that covering the entire flap area leads to better definition of the gap — an important dimensional factor in end-load compression. It may be recalled (3) that a comparative study of adhesive patterns indicated an increase of at least 16% in end-load compression strength when the adhesive was brought all the way to the exposed edge of the inner flap, as compared with normal laboratory sealing procedure.

The boxes were tested in a Baldwin-Southwark Universal testing machine at a loading rate of 0.5 in./min. The combined board was evaluated for edgewise compression strength in the machine direction, P_{mx}, by means of short columns (4-1/2 flutes high, 2 inches wide for A-flute and 1.75 inches for B-flute, edges reinforced with Carbowax 4000) at a loading rate of 0.025 in./in./min. Three sets of ten specimens of A-flute and four sets of ten specimens of B-flute were tested during the study. Flexural stiffness D_x and D_y were evaluated on twenty specimens of each sample of board by means of the four-point beam test (6-inch central span, 1-1/2-inch outer span, one-inch width) at a unit strain rate of 0.0025 in./in./min.

DISCUSSION OF RESULTS

Experiments were conducted to isolate the load carried by the flap panels and by the side panels in end-to-end compression, in order to examine the effectiveness and appropriateness of the terms in the end-load formula relating to these two types of panels. Boxes in a variety of dimensions were tested for samples of A-flute, 175-lb. series and B-flute, 275-lb. series combined board.

The average load from ten specimens is shown in Table II for each condition. In several samples of B-flute, additional specimens were tested to confirm initial results. The last four configurations for each flute construction were suggested by the results of the preceding tests and insufficient material remained for a full complement of ten specimens.

The flap-panel loads given in Table II are the maximum loads sustained by these panels in the tests where the side panels were inactive. Attention was focused on maximum load of the flap panel on the assumption that the entire box and the flap panels attain maximum load at the same instant; this is tantamount to saying that failure of the flap panels triggers failure of the box, an observation made in earlier work (4). The validity of this assumption may be examined in terms of the data of Table III which shows a comparison of the deflections of the intact box specimens and of the flap-panel specimens at maximum load of each type of structure. It may be seen that the flap-panel specimens generally reached maximum load at a deflection less than the deflection corresponding to maximum load on the intact box (hereinafter termed "box deflection"). On the average, the flap-panel deflection was 77% of box deflection for the A-flute samples and 83% of box deflection for the B-flute samples. Ordinarily this might indicate that the flap-panel loads of interest to this study should

TABLE II

RESULTS OF END-TO-END COMPRESSION TESTS ON BOXES,
FLAP PANELS AND SIDE PANELS

Sample No.	Length, L, in.	Width, W, in.	Depth, d, in.	Box Compression Strength, lb.	Flap-Panel Load, lb.	Side-Panel Load, lb.
			A-Flute, 175-lb. Series			
A1	12	9	10	420	261	--
A2	16	12	10	531	296	123(9)[a]
A3	20	15	10	618	366	--
A4	10	7.5	10	363	201	--
A5	12.5	12	10	484	410(8)	116
A6	20	12	10	554	310	118
A7	24	12	10	508	295	125
A8	16	12	6	496	--	102(9)
A9	16	12	16	494	--	160
A10	16	12	22	588	--	183
A11	12.5	12	6	558(3)	b	76(4)
A12	12.5	12	22	642(3)	b	203(3)
A13	24	12	6	460(3)	b	89(3)
A14	24	12	22	571(3)	b	165(3)
			B-Flute, 275-lb. Series			
B1	12	9	10	1123	623	--
B2	16	12	10	1286(15)	830	311(15)
B3	20	15	10	1579	800	--
B4	10	7.5	10	993	635	--
B5	12.5	12	10	1314(15)	966	340(15)
B6	20	12	10	1352	669	371
B7	24	12	10	1391(13)	661	366(14)
B8	16	12	6	1283	--	258
B9	16	12	16	1471	--	540
B10	16	12	22	1579	--	573(9)
B11	12.5	12	6	1306(4)	b	299(4)
B12	12.5	12	22	1598(4)	b	568(4)
B13	24	12	6	1166(4)	b	275(4)
B14	24	12	22	1468(4)	b	561(4)

[a] Numeral in parentheses denotes number of specimens if other than 10.

[b] Insufficient board.

TABLE III

COMPARISON OF DEFLECTIONS OF BOX, FLAP PANELS AND SIDE PANELS
AT MAXIMUM LOAD ON EACH TYPE OF STRUCTURE

Sample No.	Deflection at Maximum Load, in. Box	Flap Panel	Ratio, Flap Panel / Box	Side Panel	Ratio, Side Panel / Box
			A-Flute, 175-lb. Series		
A1	0.42	0.32	0.76	--	--
A2	0.41	0.25	0.61	0.64	1.56
A3	0.42	0.32	0.76	--	--
A4	0.41	0.32	0.78	--	--
A5	0.38	0.40	1.05	0.78	2.05
A6	0.40	0.27	0.68	0.82	2.05
A7	0.41	0.30	0.73	0.90	2.20
A8	0.41	--	--	0.94	2.29
A9	0.39	--	--	0.63	1.62
A10	0.44	--	--	0.70	1.59
A11	0.52	--	--	0.70	1.35
A12	0.49	--	--	0.73	1.49
A13	0.30	--	--	0.70	2.33
A14	0.41	--	--	0.91	2.22
Average			0.77		1.89
			B-Flute, 275-lb. Series		
B1	0.38	0.31	0.82	--	--
B2	0.35	0.30	0.86	0.63	1.80
B3	0.35	0.26	0.74	--	--
B4	0.41	0.32	0.78	--	--
B5	0.35	0.34	0.97	0.58	1.66
B6	0.36	0.28	0.78	0.57	1.58
B7	0.36	0.31	0.86	0.70	1.94
B8	0.35	--	--	0.71	2.03
B9	0.37	--	--	0.37	1.00
B10	0.38	--	--	0.39	1.05
B11	0.48	--	--	0.80	1.67
B12	0.40	--	--	0.42	1.05
B13	0.39	--	--	0.63	1.62
B14	0.36	--	--	0.38	1.06
Average			0.83		1.50
Composite average			0.80		1.69

felt that the previous experience relating to coincidence of flap panel and box failure (4) should not be ignored. That study revealed that for eight box configurations the first flap panel to fail did so at 96% of box deflection, on the average, with none of the individual values less than 89% (and none higher than 100%). Thus, for practical purposes it may be said that failure of a flap panel is virtually coincident with failure of the box. Moreover, it is believed that the different methods of loading contact for the two types of structure in the present study (flat platen for box and strips of lumber for flap-panel specimens) may give rise to some disparity in deflections, particularly at the start of the tests. For these reasons, attention was focused on maximum load supported by the flap panel. *If this choice is in fact fallacious, the error will be one of* overestimating the loads carried by the flap panels in a normal box.

Table III also lists the deflection at maximum load of the side-panel specimens (that is, with the flap panels inactive). It may be seen that the side panels attained maximum load at a deflection substantially higher than the box deflection — 189 and 150% of box deflection for A- and B-flute, respectively, and a composite average of 169%. Clearly, the maximum loads sustained by these side-panel specimens is of no significance to what happens in a normal box, because the usefulness of the box is past at the instant in question. Evidently, the side panel in an actual box acts at a load substantially lower than its potential load at the time the box fails. These results are in accord with the concept that flap-panel failure rather than side-panel failure triggers box failure in end-to-end compression. In view of the considerations, the side-panel loads listed in Table II are the loads acting on the side panels at a deflection equal to box deflection.

The observation that the side panels attained their maximum load at 169% of box deflection, on the average, appears to be in contradiction to earlier data based on load distribution measurements on one-inch segments of perimeter, as reported in Reference (1), namely, that "the perimeter scorelines...roll and crush in advance of maximum box load and support reduced loads at the time the box reaches its maximum load." That is, the load distribution work indicated maximum load on the side panels well in advance of box failure, while the present study indicates the maximum is far after box failure.

A review of the load distribution data reveals that the measurements were made on 14 by 10 by 12-inch boxes constructed with 42, 69, and 90-lb. liners in A-flute and 42-lb. liners in B-flute. Load intensity measurements were made immediately at a vertical edge of the panel, one inch in from the edge and at the middle of the panel. At the two interior locations the load clearly reached a maximum in advance of box failure, namely, at 72% of box deflection, on the average. At the time of box failure, the load had fallen off to 25 to 75% of the preceding maximum. An exception to the above trend was the load immediately at the vertical edge, which reached a maximum at 96% of box deflection and thereafter fell off to about 87% of the maximum value at the time the box failed.

A possible reconciliation of these conflicting data may be the following: In the case of the B-flute samples of the present study, 70% of the side-panel specimens exhibited a first peak in the load-deflection curve prior to the true maximum. That is, a definite relative maximum was exhibited ahead of the true maximum, the latter occurring at 169% of box deflection as mentioned above. On the average, the first peak appeared at 84% of box deflection. Thus, it is possible that the maximum observed in the load distribution work was only a relative maximum (i.e., a first peak) and the true maximum was never observed because it would have occurred beyond the test interval. However, this possible explanation is incomplete because the A-flute specimens of the present study did not exhibit a first peak in the load-deflection curve. Further study of this matter will have to be made to fully resolve the differences in these data.

As a check on the validity of the experimental procedure (cutouts and slots) employed to render given panels inactive, the sum of the flap-panel and side panel loads may be compared with the observed strength of the intact box. This comparison is shown in Table IV for those samples where all types of specimens were tested.

TABLE IV

COMPATIBILITY OF FLAP-PANEL, SIDE-PANEL AND BOX LOADS

Sample No.	Observed Box Compression Strength, lb.	Sum of Flap- and Side-Panel Load, lb.	Diff., %[a]	Ratio, Side Panel / Flap Panel
		A-Flute, 175-lb. Series		
A2	531	419	-21.1	0.42
A5	484	526	+8.7	0.28
A6	554	428	-22.7	0.38
A7	508	420	-17.3	0.42
Average			-13.1	0.38(0.46)[b]
		B-Flute, 275-lb. Series		
B2	1286	1141	-11.3	0.37
B5	1314	1306	-0.7	0.35
B6	1352	1040	-23.1	0.55
B7	1391	1027	-26.2	0.55
Average			-15.3	0.46(0.55)[b]
Composite average			-14.2	0.42(0.50)[b]

[a]Based on observed values.

[b]Ratio of load per unit width of panel.

It may be seen that, in general, the sum of the flap-panel loads and the side-panel loads does not agree closely with the observed compression strength of the box. With one exception, the sum of loads is less than the observed load. On the average, the sum was 13.1% lower for A-flute boxes and 15.3% lower for B-flute boxes. Considerable scatter exists among the eight samples.

It may be recalled from earlier discussion that if the flap-panel loads are in error, they are probably too high. However, this would not explain the disparities in Table IV. As for the side panels, the only other practical criterion for determining their loads is by taking their maximum load. This would indeed tend to remove the negative differences shown in Table IV, but, as explained above, the maximum loads on the side panels occur at deflections too large to be of significance to the compression strength of the box and hence this procedure would be physically unacceptable.

Thus, there does not seem to be a reasonable method of removing the 13 and 15% discrepancies between the sum of panel loads and observed box load. Rather it is believed that the disparities reflect that it is probably not possible to modify the structure of a box (such as was done with cutouts and slots in this work) without suffering some sacrifice in the structural integrity, and hence the strength, of the box. That is, the interaction between panels in a normal box probably is not fully preserved in these experimental structures. For this reason, the actual magnitudes of flap-panel and side-panel loads reported in this study should be viewed with some reservation. However, it is also believed that the trends exhibited by the modified structures, as dimensions are varied, can serve as a useful guide to the behavior of an intact box in end-load compression.

The right-hand column in Table IV shows the ratio of side-panel load to flap-panel load, calculated from the data of Table II. It may be seen that the ratio ranged from 28 to 55%, with an average of 38% for A-flute, 46% for B-flute and a composite average of 42%. All boxes in this comparison had a flap-panel width of 12 inches and a side-panel width of 10 inches, and thus the ratios of total load legitimately may be averaged. It is probably more meaningful, however, to examine the ratio of unit loads on each type of panel, that is, dividing each total load by the panel width and then forming the ratio. This result is given in parentheses in Table IV. On the average, the side-panel load is 50% of the flap-panel load. This is higher than was found in previous work with load distribution measurements over one-inch segments of box perimeter (1, 5), namely, 25 to 33%, although both studies are in accord that the flap panels support greater load per unit width of perimeter. The results of the present study may be rephrased as: in a box of equal width and depth in the neighborhood of 12 inches, the flap panels account for 67% of the end-load compression strength of the box and the side panels account for 33%. (The corresponding figures based on load distribution measurements are 75 to 80% for the flap panels and 20 to 25% for the side panels.) Relative to previous work, the present results indicate that the side panels support somewhat higher loads than had previously been indicated.

The remainder of this section of this report discusses the results of the three types of dimensional variation studied in this work.

EFFECT OF BOX LENGTH AT CONSTANT WIDTH AND DEPTH

An assumption made in deriving the original end-load equation [Equations (1) and (2)] was that the load carried by a side panel is independent of the length of the box (box length is the height of the side panel in the end-load orientation illustrated in Fig. 1). This assumption is based on the observation that the behavior of the side panel is mainly a crushing of the board at the body scoreline (loading perimeter) and is therefore believed to be a function of scoreline geometry and crush strength of the combined board rather than the gross height of the panel. For this reason, box length does not appear in the side-panel term of the formula. The present phase of the cut-away panel study was directed to examining this assumption.

Table V presents side-panel load and box compression strength extracted from Table II and arranged to facilitate study of the effect of box length. With regard to the experimental design, the effect of box length in the range of 12.5 to 24 inches was studied at each of three box depths (6, 10, and 22 inches), all at a constant box width of 12 inches.

With reference to the side-panel loads, the effect of box length is shown graphically in Fig. 4. It may be seen that at any given box depth there is no consistent trend for side-panel load to vary with box length. An analysis of variance [appropriate to unequal sample sizes (6)] was performed on the data at each depth. It should be noted that an analysis of variance tests the hypothesis that the panel loads do not differ significantly from the average for all lengths at a given depth (the average is shown as a dashed line in Fig. 4); it does not, however, speak to the matter of trends for panel load to vary progressively with length if significant differences exist. Such trends may be inspected visually rather than statistically.

The statistical analysis revealed that there was no significant variation of side-panel load with change in box length (0.05 level of significance), except in the case of the 6-inch depth A-flute boxes and the 10-inch depth B-flute boxes. Thus, in four out of six cases the deviation of the side-panel

TABLE V

EFFECT OF BOX LENGTH AND BOX DEPTH ON SIDE-PANEL LOAD AND BOX COMPRESSION STRENGTH
(Box Width = 12 inches)

	Side-Panel Load, lb.							
	A-Flute, 175-lb.				B-Flute, 275-lb.			
Depth:	6	10	16	22	6	10	16	22
Length								
12.5	76	116	--	203	299	340	--	568
16	102	123	160	183	258	311	540	573
20	--	118	--	--	--	371	--	--
24	89	125	--	165	275	366	--	561
Average	93	120	160	183	271	344	540	569

	Box Compression Strength, lb.							
	A-Flute, 175-lb.				B-Flute, 275-lb.			
Depth:	6	10	16	22	6	10	16	22
Length								
12.5	558	484	--	642	1306	1314	--	1598
16	496	531	494	588	1283	1286	1471	1579
20	--	554	--	--	--	1352	--	--
24	460	508	--	571	1166	1391	--	1468

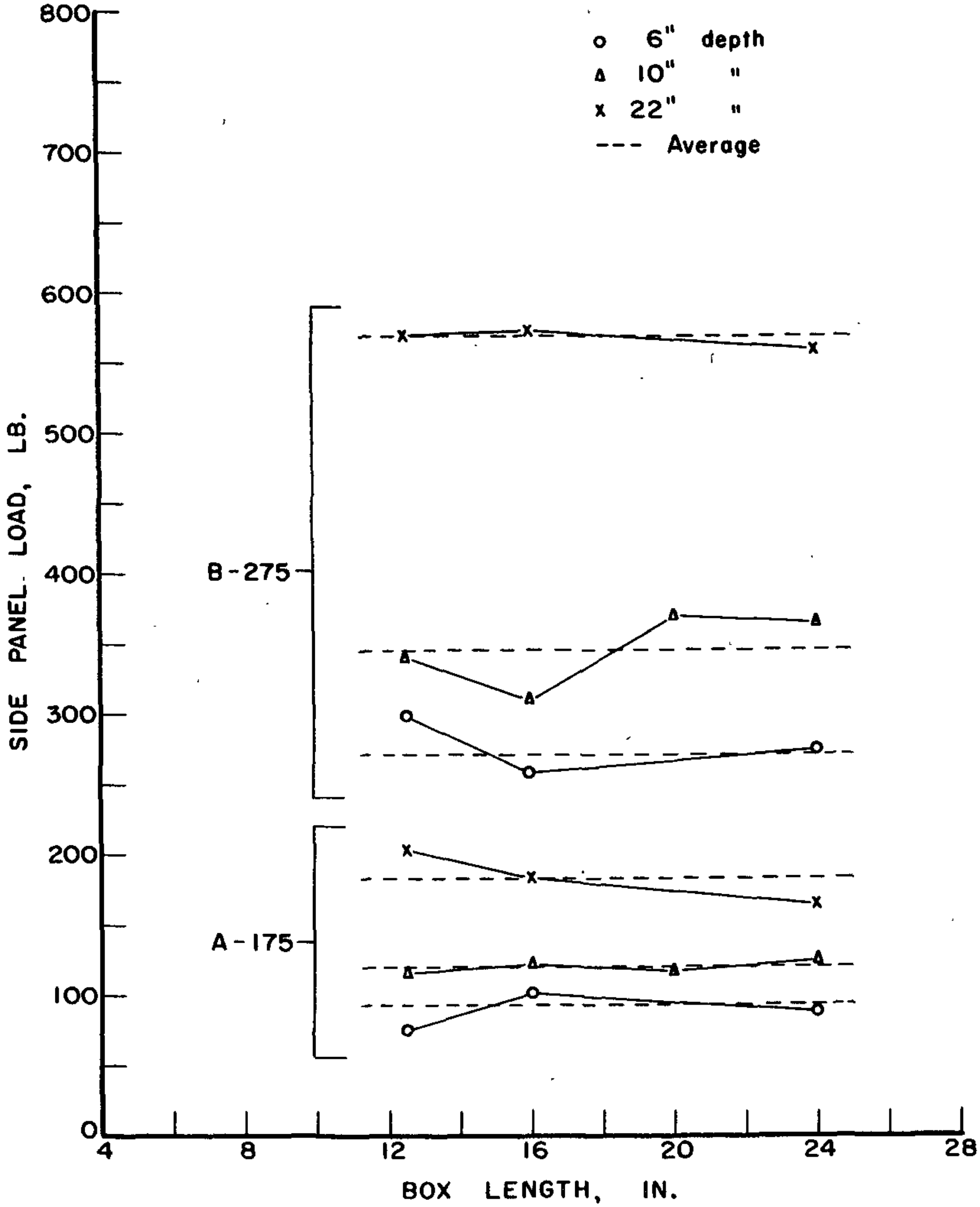

Figure 4. Effect of Box Length on Side-Panel Load at Various Box Depths (Width = 12 Inches)

load from the average for all box lengths may be attributed to chance as a consequence of the inherent variation in the compression tests of side panels. (The standard deviation of the compression tests ranged from 10.8 to 14.2% of the side-panel load.) Of the two exceptional cases, the B-flute results exhibit a "zig-zag" pattern in Fig. 4 and it is difficult to conceive of a physical reason for this occurring. Despite the statistical results, it is questionable whether length should be considered to be a governing factor in the load supported by these particular side panels. In the case of the A-flute, 6-inch depth specimens, the significant deviations admit the possibility of a maximum in side-panel load at an intermediate length although the effect is not large. All things considered, it appears that in four and possibly five cases out of six, there is no consistent trend for panel load to vary with box length. It seems safe to conclude, therefore, that the load supported by the side panels of a box in end-load compression is independent of box length, as has been assumed in past work.

Figure 5 shows the <u>flap-panel</u> load for four box configurations where the box width and box depth were held constant at 12 and 10 inches, respectively, and the length was varied from 12.5 to 24 inches. The data are shown in Table II (Samples 2, 5, 6, and 7). It may be seen that, in general, flap-panel load decreases with increasing box length, as would be expected. As the length increases (at constant box width) the gap between inner flaps increases and the flap panel becomes structurally weaker overall. Since the loading perimeter of this panel is constant in this case, the total load on the panel decreases with increasing length. As discussed in Reference (1), the end-load formula is in agreement with this trend. The dashed-line curves in Fig. 5 are the estimated loads for flap panels of these particular combined board samples, as evaluated from the flap-panel term in the end-load formula [Equation (2), Introduction, based on Carbowax 4000 test for P_{mx}]. In this calculation and elsewhere in

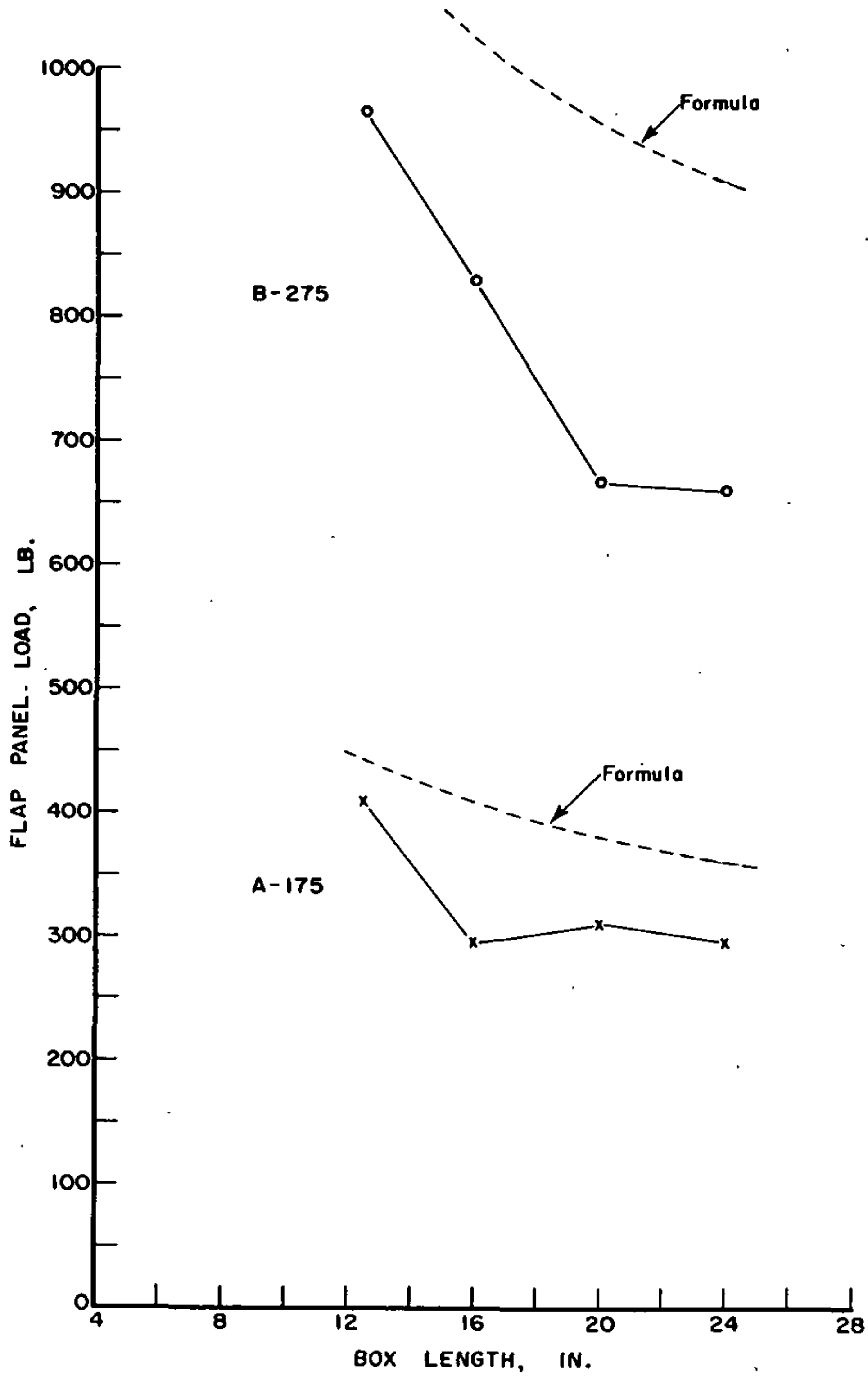

Figure 5. Effect of Box Length on Flap-Panel Load
(Width = 12 Inches; Depth = 10 Inches)

this report the mechanical properties of the samples are as tabulated in Table VI. It may be seen that, although showing the same trends as the experimental data, the formula substantially overestimates the flap-panel load of these samples. Further discussion of this point will be made later in connection with other data. At any rate, the experimental data indicate that there is a decrease in flap-panel load as box length increases, indicating that length is a necessary factor in the flap-panel term, though not the side-panel term, of an end-load formula.

TABLE VI

MECHANICAL PROPERTIES OF COMBINED BOARD

Flute	Series, lb.	P_{mx}, lb./in.	D_x, lb.-in.	D_y, lb.-in.
A	175	19.3	150	88.3
B	275	68.1	116	56.7

The effect of box length on the end-to-end compression strength of the entire box is shown in Table V and Fig. 6. In four of six cases there is a clear trend to decreasing box strength with increasing box length, as anticipated (since the effect of length on box strength should be the sum of the effects discussed above for the side panels and the flap panels). In two instances, however, the box behavior exhibits a contrary trend. In the case of the exceptional B-flute samples, retests were performed on three of the box configurations, but essentially the same trend was exhibited. These two exceptional instances constitute an unexpected result, for which no explanation can be offered at this time. The dashed curve in Fig. 6 is the end-load formula evaluated at a depth of ten inches – the intermediate depth of the three studied here. Evidently the formula underestimates the observed loads, but otherwise exhibits a trend generally compatible with four of the six experimental curves of Fig. 6.

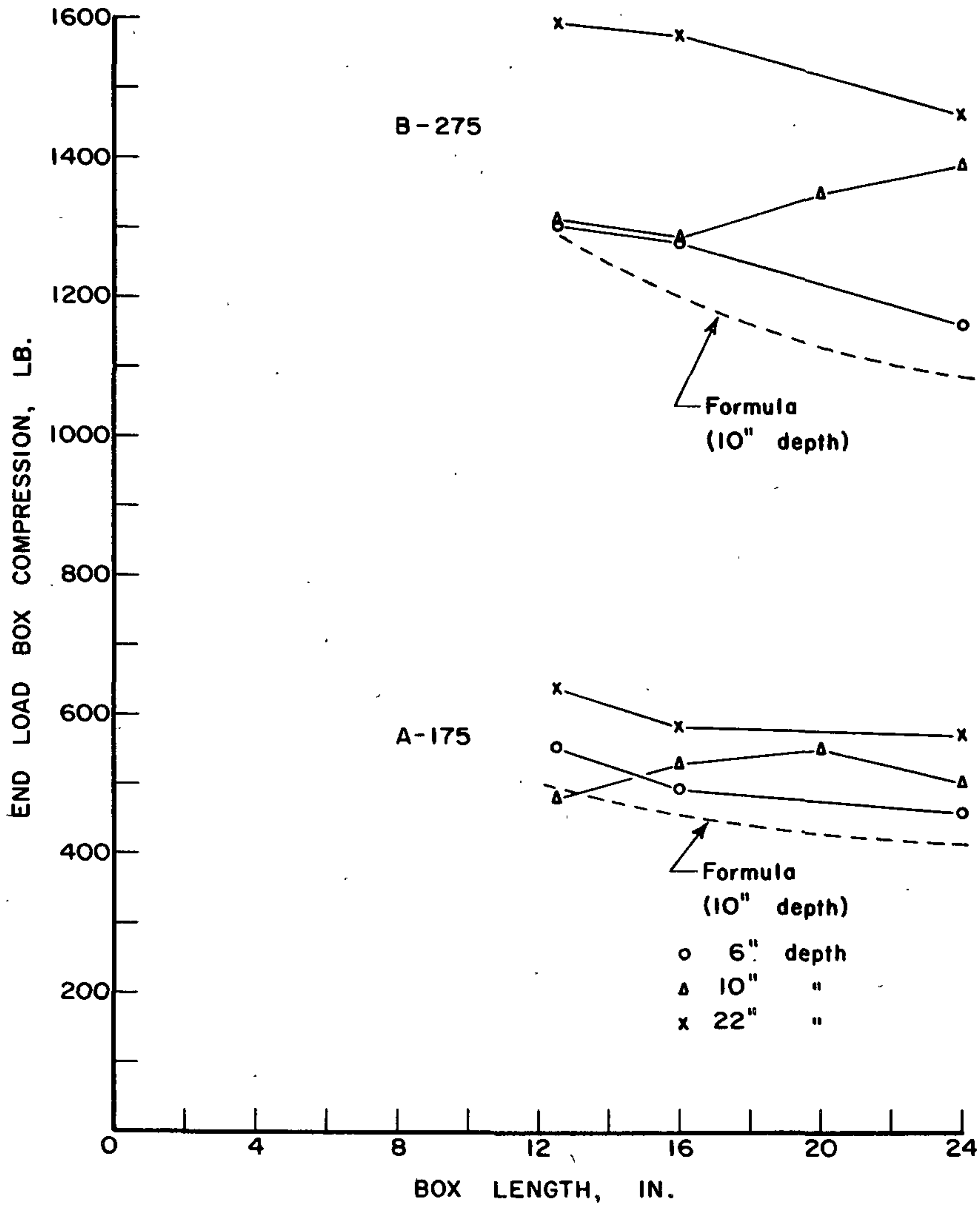

Figure 6. Effect of Box Length on End-to-End Box Compression Strength at Various Box Depths (Width = 12 Inches)

Taken in its entirety, the preponderance of evidence in this portion of the study indicates the following trends:

(a) Side-panel load is independent of box length.

(b) Flap-panel load decreases with increasing box length (at constant box width) because of the increase in the gap.

(c) Box compression strength decreases with increasing box length because of the aforementioned behavior of the flap panels.

EFFECT OF BOX DEPTH AT CONSTANT LENGTH AND WIDTH

As mentioned earlier, it was assumed in deriving the end-load formula that the total load supported by the side panels at failure of the box is directly proportional to the width of the side panels — that is, proportional to the depth of the box. In addition it was assumed that the intensity of load on the side panel is uniform across the panel and equal to a fractional part of P_{mx}, on the grounds that the mechanism of crushing at the scoreline (loading perimeter) has similarity to failure of combined board in machine-direction edgewise compression. The assumption of uniformity of load across the side panel appears to be a reasonable approximation for a large portion of the panel loading perimeter, based on load distribution measurements (5). However, these measurements indicate that over one inch of perimeter immediately adjacent to the corner, the load intensity is substantially higher than over the remainder of the panel, suggesting that the vertical edge is a strengthening element as in the case of flap panels (or as in all panels in top-load compression). The data of this experiment permit examination of the appropriateness of these assumptions.

The effect of varying box depth on side-panel load and box compression strength may be studied in terms of the data of Table V and Fig. 7 and 9. Box

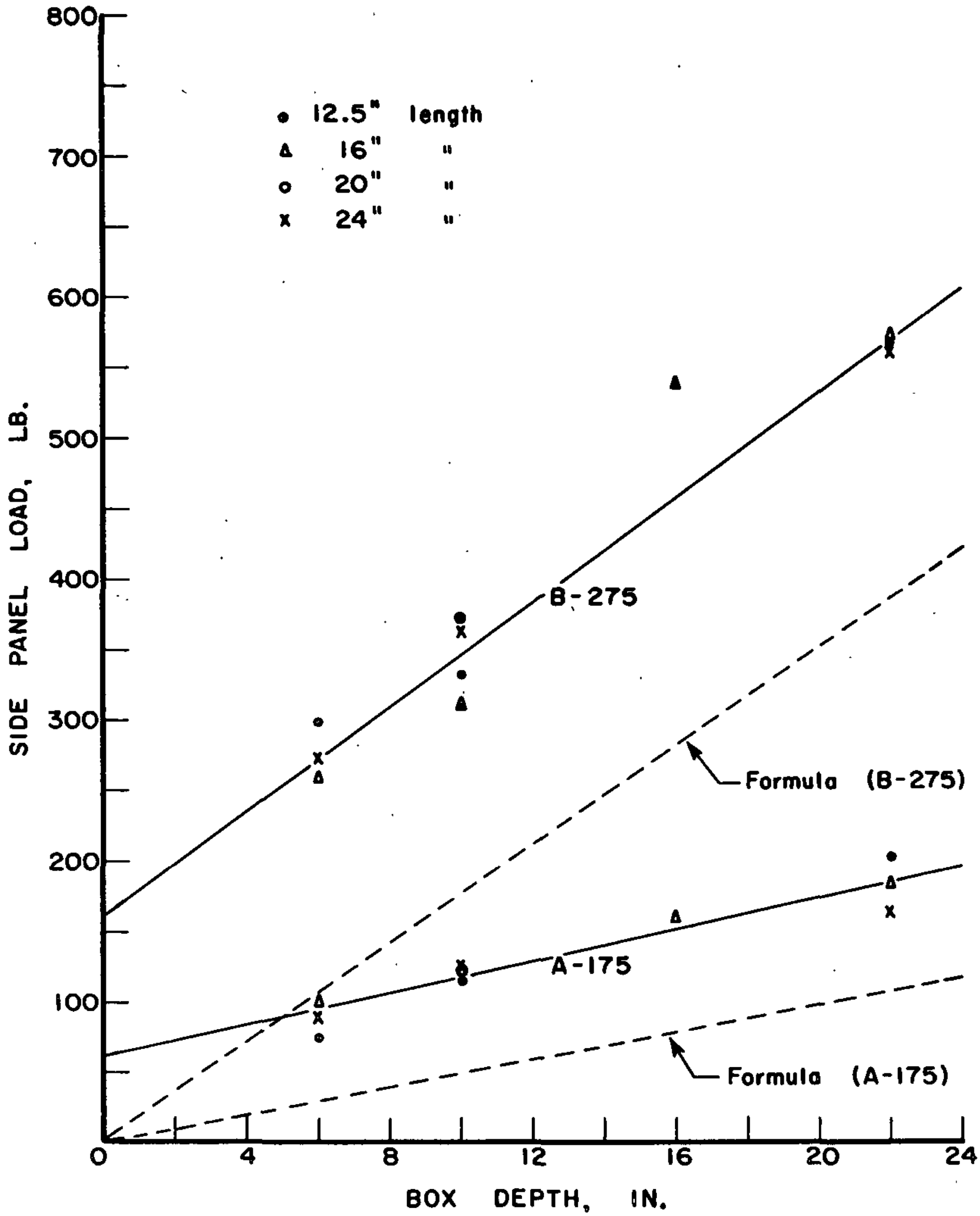

Figure 7. Effect of Box Depth on Side-Panel Load at Various Box Lengths (Width = 12 Inches)

depth is varied over the range of six to 22 inches at each of three box lengths (at constant box width).

With reference to the side-panel loads, Fig. 7 reveals that load varies approximately linearly with box depth. At a given depth there are several points representing various box lengths for a given combined board construction. It may be recalled from the preceding section of this report that side-panel load is independent of box length. Figure 7 illustrates this same point, inasmuch as there is intermingling of points with no indication that a curve for one box length lies consistently above or below that for another length.

Straight lines were fit to the A- and B-flute data of Fig. 7 by the method of least squares (weighting each point according to the number of specimens determining the point). With reference to Equations (1) or (2) in the Introduction, the structure of the term for side-panel load, P_s, is [see also (1)]:

$$P_s = 2fP_{mx}\,d \tag{3}$$

whereupon the slope of a line in Fig. 7 provides an estimate of $2fP_{mx}$ and hence of $2f$, the latter being the numerical coefficient of the side-panel term. It was found that the estimates of $2f$ for these combined boards (and their 95% confidence limits) are:

A-flute, 175-lb.: $2f = 0.290 \pm 0.036$

B-flute, 275-lb.: $2f = 0.274 \pm 0.036$

These estimates are very close to the numerical coefficient, 0.260, of the side-panel term in Equation (2) (the end-load formula for Carbowax 4000 evaluation of P_{mx}). This result indicates that, in so far as dependence of box depth d is concerned, the side-panel term of Equation (2) is appropriate to the experimental structures of the present study.

However, the end-load formulas previously derived assumed that side-panel load is proportional to depth, whereas the curves of Fig. 7 reveal that there is a sizable intercept. That is, for these experimental specimens, side-panel load varies linearly with depth but is not directly proportional to depth. These results indicate that the side-panel term in the formula should be of the form:

$$P_s = 2fP_{mx} d + \text{Constant} \qquad (4)$$

in order to adequately describe the experimental side-panel loads. Moreover, it may be noted that the constant (that is, the intercept in Fig. 7) is considerably higher for the B-flute construction than for the A-flute board. Further examination indicated that the magnitude of the intercept appears to be related to the magnitude of P_{mx}. This is shown in Fig. 8, which is a graph of the intercept of Fig. 7 vs. P_{mx} of the two samples of combined board. This graph suggests the possibility that the intercept [i.e., the constant in Equation (4)] might be approximated by qP_{mx}, where q is the slope of the line of Fig. 8. This states that the constant in Equation (4) is proportional to P_{mx}. While a curve of higher order than a straight line might be fitted to Fig. 8, consideration of the small number of points and a desire for as much simplicity in the side-panel term as is possible, favor approximation by a straight line. Accordingly, a suggested amendment of the side-panel term in the end-load formula is:

$$P_s = 2fP_{mx} d + qP_{mx} \qquad (5).$$

Regarding likely values of q, the slope of the line in Fig. 8 gives $q = 2.58$. There is, of course, some uncertainty in the best location of the line in Fig. 8. The ordinates of the plotted points, which are the intercepts

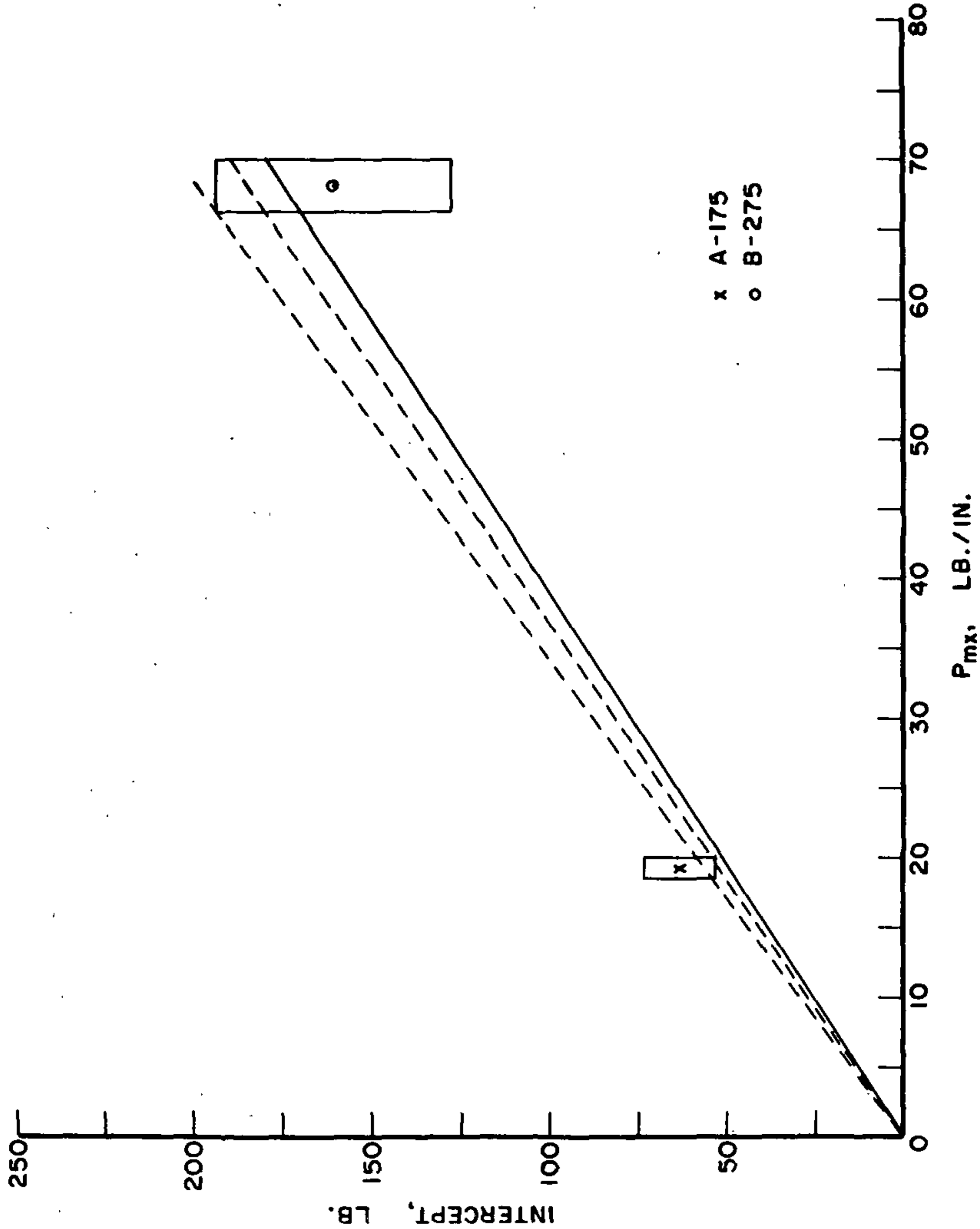

Figure 8. Relationship Between the Intercepts of the Straight Lines in Fig. 7 and P_{mx}

of Fig. 7, have uncertainty because of the variability of loads in Fig. 7. Moreover, the abscissae of Fig. 8 have uncertainty because they are $\underline{P}_{\underline{mx}}$ and are subject to experimental variability. Approximate confidence limits with respect to both sources of variation may be constructed about the points of Fig. 8, shown as rectangles centered on the point. The base and the height of each rectangle represents a 95% confidence limit, whereupon it may be stated that there is approximately 90% confidence that the true value of the plotted point lies within the rectangle.

The solid line constructed in Fig. 8, which is a least squares fit through the origin, just misses the confidence rectangle of the A-flute point. Alternatively, lines through the origin which fall within both confidence limits may be considered; the extremes are shown dashed in Fig. 8. They correspond to values of $\underline{q}$ between 2.72 and 2.92. Values of $\underline{q}$ in this range may be expected to give an adequate estimate of side-panel load for specimens of this study. In summary, based on this study it appears that the side-panel term should be revised to the form given by Equation (5), with 2$\underline{f}$ expected to be in the range of about 0.23 to 0.32 and $\underline{q}$ in the range of about 2.7 to 2.9.

The proper physical interpretation to be placed on the proposed amendment to the side-panel term in the end-load formula is not entirely clear at this point. On the one hand, the term $\underline{q}\underline{P}_{\underline{mx}}$ may reflect the higher intensity of load that has been observed at the vertical edge of the side panel (5). Thus, as the box depth approaches zero, the side panel becomes two sturdy vertical edges that support load out of proportion to the small width of the panel. On the other hand, it may be that the curves appropriate to Fig. 7 are really curvilinear through the origin, but are approximated well by straight lines in the range of depths from 6 to 22 inches. The former explanation is regarded as the more likely.

Returning to Fig. 7, the dashed lines through the origin represent the estimated load on the side panels, based on Equation (2). It is seen that the formula substantially underestimates the side-panel load (by the amount of the intercept discussed above). It was mentioned earlier in connection with Fig. 5 that the flap-panel term in the formula considerably overestimates the strength of the flap panels. These observations indicate that the empirically derived formula attaches too much importance to the flap panels and too little to the side panels of the box.

The effect of box depth on end-load compression strength is shown graphically in Fig. 9. It may be seen that box load appears to vary linearly with box depth — a result which is compatible with the data of Fig. 7 for side panels alone. On the theoretical grounds, a line should be fit to the data for each individual box length in Fig. 9 to account for the effect of box length on flap-panel load. However, the length effect seems to be obscured by variability in the data. Therefore, a single straight line was fit to the data for each flute construction, representing the effect of box depth on end-load at an "average" box length. The slopes of these lines give the following estimates of the numerical coefficient, $2\underline{f}$, of Equations (3) or (5):

A-flute, 175-lb.: $2\underline{f} = 0.294 \pm 0.226$

B-flute, 275-lb.: $2\underline{f} = 0.283 \pm 0.090$

The nominal values of these estimates of $2\underline{f}$ are nearly identical with the estimates from the side panels discussed above, indicating compatibility of results from the two types of corresponding structures. The confidence limits in the present case, however, are very wide, reflecting the averaging over several box lengths. The intercepts of the fitted lines in Fig. 9 represent the contribution from the flap panels. The dashed lines in Fig. 9 represent the end-load formula [Equation (2)]

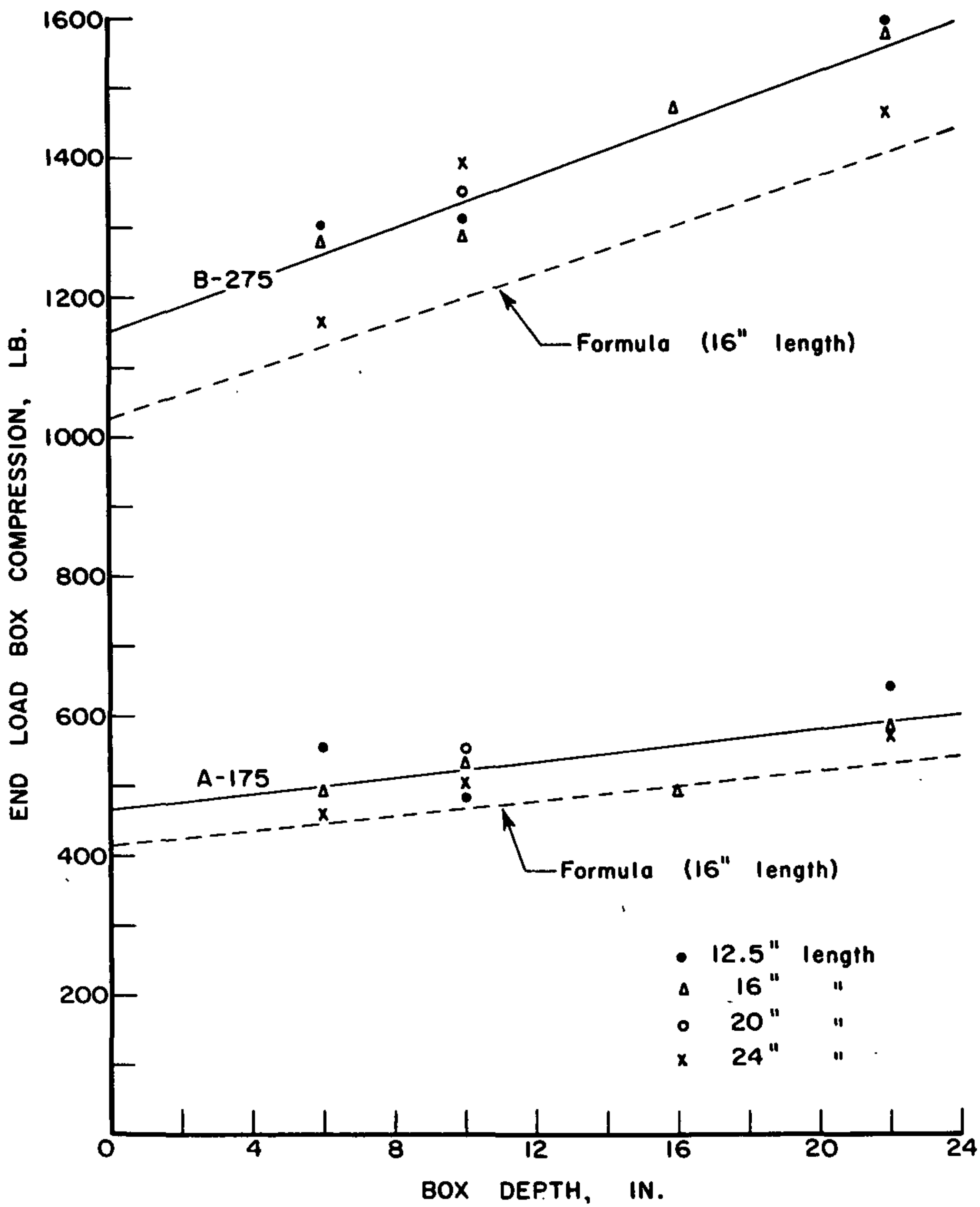

Figure 9. Effect of Box Depth on End-to-End Box Compression Strength at Various Box Lengths (Width = 12 Inches)

evaluated for a box length of 16 inches. It may be seen that the formula parallels the experimental data but systematically underestimates the compressive strengths of these experimental boxes, as was the case for the side panels alone (Fig. 7). Thus, the box strength data appear to be compatible with the side-panel data.

In summary, for the study of the effect of box depth, it was found that:

(a) the load carried by a side panel varies linearly with box depth (width of panel) over the range of depths from 6 to 22 inches;

(b) the factor of proportionality in the above relationship is a constant fractional part of $\underline{P}_{\underline{mx}}$ and is in good numerical agreement with the end-load formula.

(c) However, the end-load formula underestimates the load carried by the side panels; it appears that the formula can be brought into agreement with these experimental data by amending the side-panel term to:

$$P_s = 2fP_{mx}\,d + qP_{mx}$$

where $\underline{q}$ is a constant in the range of about 2.7 to 2.9.

(d) This study indicates that the earlier end-load formula [Equation (2)] underestimates the load carried by the side panels and overestimates the load carried by the flap panels.

EFFECT OF VARYING BOX LENGTH AND WIDTH AT CONSTANT RATIO $\underline{W}/\underline{L}$ = 0.75 AND AT CONSTANT DEPTH

It was shown above that flap-panel strength decreases with increasing box length at constant box width and depth, due to the increasing gap between inner flaps. Suppose, on the other hand, that both the box length and box width are increased. Two opposing effects may occur: (a) the gap may increase (if length is increased more than the width) which tends to weaken the panel, and (b) the loading perimeter of the flap panel increases (because of increase in box width) which tends to increase the total load carried by the box. The question is: which effect dominates the other, that is, will box load increase or decrease?

This case of dimensional variation was discussed in Reference (1) because it was believed to be a critical test of the appropriateness of the end-load formula. It was shown that the formula predicts an increase in box strength, that is, that the effect of increasing width dominates the effect of increasing gap (for the well-defined case of a constant ratio of width to length, which involves an increasing gap).

The present study enables experimental evaluation of this particular dimensional variation. Samples 1, 2, 3, and 4 in either flute construction represent boxes of varying length and width at constant depth $\underline{d}$ = 10 inches, but with length and width maintained in the constant ratio of $\underline{W}/\underline{L}$ = 0.75. The flap gap increases from 2.5 to 5 inches in this series of samples. The loads carried by the flap panels and the box compression strengths are shown graphically in Fig. 10 and 11. The abscissa is plotted in terms of box width, but could equally well be plotted as box length since these two dimensions are maintained proportional.

With reference to Fig. 10, it may be seen that the load carried by the flap panels increased with increasing box width and length (although somewhat erratically in the case of B-flute). This means that the effect of increasing

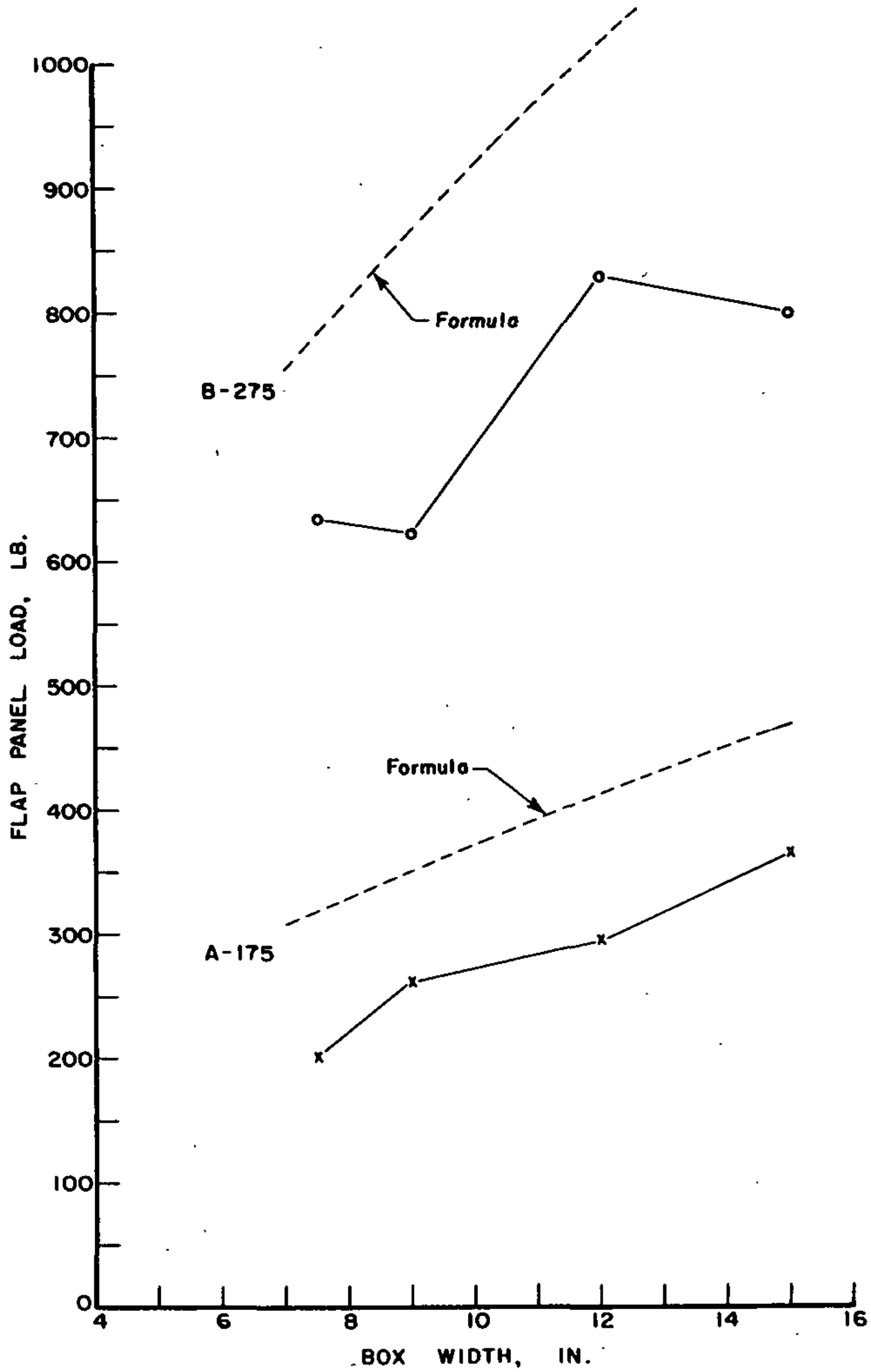

Figure 10. Effect on Flap-Panel Load of Varying Box Length and Width (W/L = 0.75; Box Depth = 10 Inches)

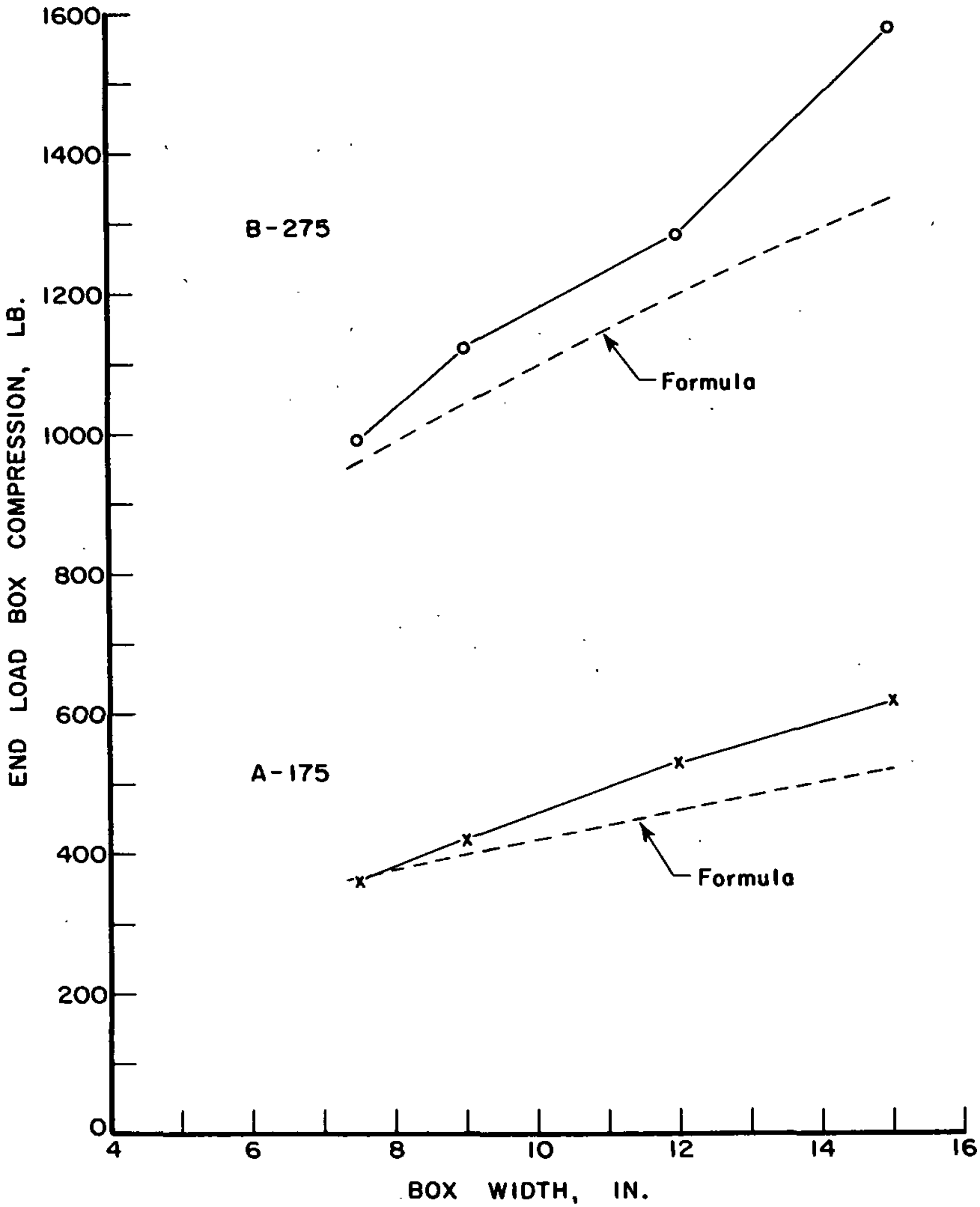

Figure 11. Effect on End-to-End Box Compression Strength of Varying Box Length and Width ($\underline{W}/\underline{L}$ = 0.75; Box Depth = 10 Inches)

the flap-panel perimeter more than offset the loss in load due to increasing gap, giving a net increase in the flap-panel load.

The end-load formula is in agreement with this trend, although the formula (shown dashed in Fig. 10) overestimates the load carried by the flap panels, as in preceding phases of this study. This systematic overestimation could be adjusted by modification of the multiplying coefficient of the flap-panel term in the formula. Of more immediate interest is whether the functional dependence of panel load on box width W is adequate in the formula. To address the question, a power function W^a was fit to the data of Fig. 10 for each flute size, where a is a constant. This is the functional dependence appearing in the formula inasmuch as all other factors in the flap-panel term are constant in this phase of the experimental work. The exponent a evaluated to 0.800 for the A-flute sample and 0.430 for the B-flute sample, as compared with 0.571 in Equation (2). Although the estimate for each flute size is considerably at variance with the exponent of the formula, some allowance perhaps should be made for the small number of points in Fig. 10. Also, it might be noted that both estimates are less than unity as expected and the average of the estimates is 0.615 which agrees reasonably well with the value 0.571 from the formula.

The end-to-end box compression strength under this type of dimensional variation is shown graphically in Fig. 11. The data appear more orderly than for the flap panels alone. The data indicate increasing box strength with increasing width and length, confirming the aforementioned conclusion that the perimeter effect dominates the gap effect. The formula (dashed curve) appears to be in reasonably good agreement with the trend of the experimental data, although there is in general an underestimation of the observed loads.

There are, of course, other ways of varying length and width than were studied here and which might warrant study. For example, length and width could be increased in such a way that the flap gap stays constant (this corresponds to increasing the ratio $\underline{W}/\underline{L}$). The end-load formula predicts an increase in box compression for this case because the perimeter increases and the flap gap becomes a decreasing fraction of the panel height (that is, $\underline{W}/\underline{L}$ increases).

In summary, the study of varying box length and width revealed the following:

(a) Flap-panel load, and consequently end-to-end box compression strength, increases with increasing box length and width (at constant $\underline{W}/\underline{L} = 0.75$ and constant box depth).

(b) The aforementioned result indicates that the effect of increasing the loading perimeter of the flap panel dominates the effect of increasing the gap under this type of dimensional variation.

(c) The end-load formula is in agreement with these trends, although the formula overestimated the load carried by the flap panels.

Reference to Fig. 4 to 11 covering all phases of this study reveals that the end-load formula consistently (a) overestimates flap-panel load, (b) underestimates side-panel load, and (c) underestimates box compression strength. Underestimation of the side-panel load has been discussed at some length and a modification is suggested for the side-panel term of the formula that can be expected to bring the predicted and observed loads on the side panel into better agreement.

In view of the underestimation of side-panel load with the present formula, it should be expected that the formula overestimates the flap-panel load, for the following reason: the constants of the formula were determined to give the best over-all agreement with compressive strength of a number of commercial boxes; if, through a deficiency in the structure of the formula, the load carried by one portion of the box is underestimated, then the load carried by the remaining portion of the box must be overestimated in order to give over-all agreement with box compression. Thus, the error in predicting side- and flap-panel loads are complementary.

The reason for consistent underestimation of the compressive strength of the boxes of this study is less obvious. For the reason given above, errors in the relative contribution of flap- and side-panels could exist without necessarily causing systematic error in the estimates of box load; apparently this has been the case with the commercial samples of References (1) and (2).

It is believed that the systematic underestimation of the box strengths in this study is attributable to the change in flap sealing procedures, described in TEST PROCEDURE. It seems likely that the more reliable adhesion between flaps and the greater adhesive coverage used in this experiment gave a higher level of box performance than was achieved with the commercial box samples used in earlier work. Inasmuch as the numerical coefficients in the end-load formula reflect the earlier work, it is understandable that the formula could systematically underestimate box loads in the present study.

FUTURE WORK

The results of this study lend confidence to the structure of the end-load compression formula relative to the effect of box dimensions. A number of assumptions made in deriving the end-load formula appear to be justified by the results of this study. Specifically, box length appears to have little if any effect on the side-panel load, as has been assumed. The assumption that the intensity of load on the side panel is a fractional part of P_{mx} is supported by the data. The formula appears to be in agreement with the effect of box length and width on the flap-panel load, although it should be remarked that the present study did not concentrate heavily on the flap panels — the main emphasis was on the side panels.

As discussed above, the major innovation stemming from this work is a suggested modification of the side-panel term in the end-load formula. The data indicate that, while side-panel load varies linearly with depth, it is not directly proportional to depth. Another additive term in the formula, depending on combined board strength, is indicated. Work in the immediate future will be directed to incorporating this modification into the end-load formula. This involves re-evaluation of the numerical coefficients of the formula, the focal point being whether this improves the accuracy of the formula for a collection of commercial box samples previously studied.

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